The Metric System:
An Introduction

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MASTER

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Part 1: Basics of the Metric System

Part 2: Applying the Metric System

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Part 1: Basics of the Metric System

1.1 Motivation for Learning about the Metric System

Why is LLNL converting to the metric system?

On July 13, 1992, Deputy Director Duane Sewell restated the Laboratory's policy on conversion to the metric system which was established in 1974. Sewell's memo announced the Laboratory's intention to continue metric conversion "on a reasonable and cost effective basis". Copies of the 1974 and 1992 Administrative Memos are contained in the Appendix.

There are three primary reasons behind the Laboratory's conversion to the metric system. First, Public Law 100-418, passed in 1988, states that by the end of fiscal year 1992 the Federal Government must begin using metric units in grants, procurements, and other business transactions. Second, on July 25, 1991, President George Bush signed Executive Order 12770 which urged Federal agencies to expedite conversion to metric units. Third, the contract between the University of California and the Department of Energy calls for the Laboratory to convert to the metric system. Thus, conversion to the metric system is a legal requirement and a contractual mandate with the University of California.

Public Law 100-418 and Executive Order 12770 are discussed in more detail later in this section, but first we examine the reasons behind the nation's conversion to the metric system.

Why is the United States converting to the metric system?

The world order is changing. Germany has been re-united, the Soviet Union no longer exists, and the European Union has emerged as the world's largest market. Trade has become increasingly important, and increased trade makes nations more dependent upon one another.

Technology is making our world smaller. Satellites beam down television signals enabling us to witness historic events as they unfold halfway around the world. FAX machines give us the ability to exchange documents anywhere on earth in a matter of seconds. Cellular phones are so common we see people using them while walking on the street and in shopping malls—not just in their cars.

Trade and technology are two forces pushing nations to work together to develop and use world-wide standards. One area where standardization is beginning to impact our daily lives is that of measurement. **The world standard system of measurement is the metric system**. The metric system has been adopted by every major country in the world—except the United States. World markets are almost exclusively metric. The ability of U. S. industry to compete in those markets depends, in part, on designing and producing metric goods. **Converting to the metric system has become an economic necessity.**

Who is responsible for determining our system of measurement?

The Constitution gives Congress the power to fix uniform standards of weights and measures. The Department of Commerce is charged with the technical responsibility of defining and maintaining those standards, which is handled through the **National Institute of Standards and Technology**, or NIST. (NIST was formerly known as the National Bureau of Standards.)

Is the idea to convert to the metric system new?

The idea of converting to the metric system is not new. In fact, it has been discussed and debated for almost 200 years. But the need for the United States to convert to the metric system became crystal clear on May 24, 1965, when the President of the British Board of Trade announced in Parliament the United Kingdom's intention to convert to the metric system [1, page 21]. This decision was necessary for Britain to join the Common Market. Since that time it has become increasingly apparent that U. S. companies must convert to metric units in order to compete in world markets.

In 1968, Congress passed the **Metric Study Act** which authorized the Secretary of Commerce to study the implications of metric conversion. In 1971, Secretary Maurice Stans submitted a report to Congress containing the results of this comprehensive, three-year study. The report was entitled **A METRIC AMERICA: A decision whose time has come**.

What Federal legislation was passed that relates to metric conversion?

In response to the Secretary's report, Congress passed the **Metric Conversion Act** which was signed into law by President Gerald Ford in December, 1975. In 1976, we began to see and feel the results of this act. Road signs appeared showing distances to cities in both miles and kilometers. (There is a sign on eastbound I-580 that shows Livermore — 17 miles, 27 kilkometers.) Most gas stations displayed price per gallon and price per liter. (In fact, the *Flying Ram* gas station on First Street in Livermore actually pumped gas by the liter in 1976.) School systems began to teach metric units, and we were told that soon everyone would be using the metric system.

But the predicted conversion never happened! Under the Metric Conversion Act **conversion was optional**. Most people felt more comfortable with familiar units such as inches, pounds, and gallons. Conversion was viewed as painful and expensive. As a result, most visible signs of metrication disappeared after only a short time, and the push toward metric conversion seemed to be just a fad.

Although metrication disappeared from public view, the need for metrication did not disappear. In fact, the need for metrication became more acute.

Despite its apparent failure, the Metric Conversion Act produced some positive results. Many companies became aware of the need to convert to metric units in order to remain competitive in world markets. Others saw that metrication was the way of the future, and metric units were introduced in new products. The automobile industry, the alcohol industry, and many companies began to design and build products to metric standards.

On August 23, 1988 Congress passed **Public Law 100-418**. This law was part of the Omnibus Trade and Competitiveness Act and amended The Metric Conversion Act passed in 1975. Public Law 100-418 states in part:

It is therefore the declared policy of the United States—

> *(1) to designate the metric system of measurement as the preferred system of weights and measures for United States trade and commerce.*
>
> *(2) to require that each Federal agency, by a date certain and to the extent economically feasible by the end of the fiscal year 1992, use the metric system of measurement in its procurements, grants, and other business-related activities, except to the extent that such use is impractical or is likely to cause significant inefficiencies or loss of markets to United States firms, such as when foreign competitors are producing competing products in non-metric units.*
>
> *(3) to seek out ways to increase understanding of the metric system of measurement through educational information and guidance and in Government publications; and*
>
> *(4) to permit the continued use of traditional systems of weights and measures in non-business activities.*

An important difference between the Metric Conversion Act and Public Law 100-418 is that **Public Law 100-418 makes metric conversion mandatory for the Federal government.**

The Executive Branch joined the metrication effort on July 25, 1991, when President Bush signed **Executive Order 12770**. EO 12770 directs departments and agencies to expedite the transition to metric units. Agency transition plans are now being implemented, and the transition has begun. The Clinton administration also has supported metric conversion.

The impact of Public Law 100-418 goes well beyond the Federal government. State and local governments must begin using metric units in their contracts with the Federal government. Companies that supply products to the Federal government also will have to convert to metric units. Thus, metrication is starting to become a reality for millions of people across the country.

1.2   Origin of the Metric System

What is the origin of the metric system?

In the United States we use the **inch-pound** system. It was brought here by early settlers hundreds of years ago, and it is similar to the system of units that was used in England.

The **metric system** is much newer. It was developed in France about 200 years ago. At the time, France was the leading scientific nation in the world, yet its system of units was inconsistent. For example, one unit, the *pied*, or foot, varied in size from one city to

another. Using the size of the pied in Paris as a standard (that is, 1.0 unit), the size of the pied in several other cities is shown below:

| Lyon | 1.05 | Bordeaux | 0.92 |
| Monaco | 0.72 | Lorraine | 0.90 |

Imagine how chaotic life would be in the United States if the size of a foot in Washington, New York, Chicago, and San Francisco were all different!

In 1790, the National Assembly of France asked the French Academy of Science to develop a new system of measurement. The new system was to be based on facts of nature, and it was to be suitable for use by the entire world.

The original metric system consisted of units for length, mass, volume, and area. The fundamental or stem unit of length was called the **meter**. It was defined as one ten-millionth of the great circle distance from the north pole to the equator.

north pole

meter: one ten-millionth of the great circle distance fromt the north pole to the equator
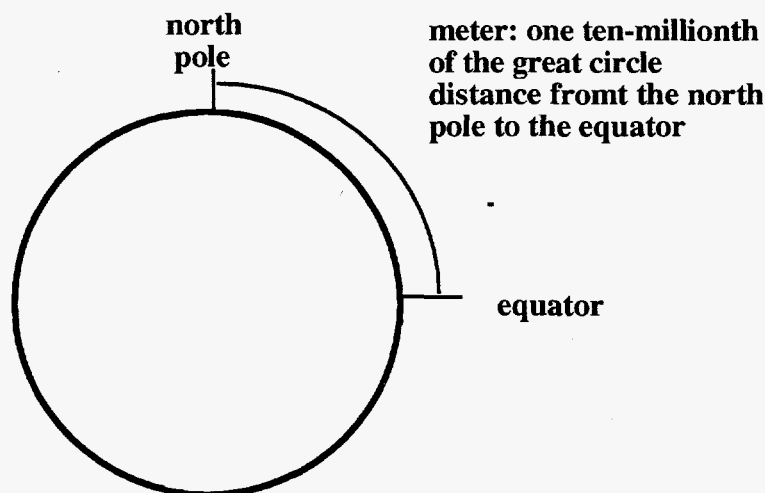
equator

Figure 1: Definition of the meter.

The stem unit for mass was the **gram**. A gram was defined as the mass of a cube of pure water, one-hundredth of a meter on each edge. The water was to be the temperature of maximum density (slightly above freezing).

gram: mass of a cube of pure water where s = 0.01 meter
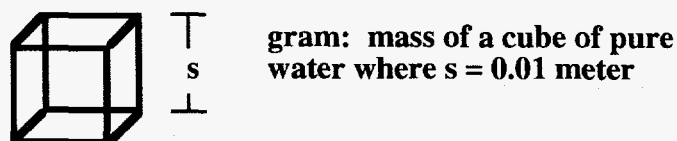
Figure 2: Definition of the gram.

The term *mass* may be somewhat unfamiliar. Mass refers to the amount of material. We often use the word *weight* in place of mass. But weight may also mean *force*. Force is mass times acceleration. Thus, mass and force are two different kinds of units. Since weight may mean either mass or force, it can be both ambiguous and confusing.

The stem unit for volume was the **liter**. A liter was defined as the volume of a cube which is one-tenth of a meter on each edge. The liter was used to measure volumes of fluids. Units for dry volumes are discussed in the next section.

liter: volume of a cube where s = 0.1 meter
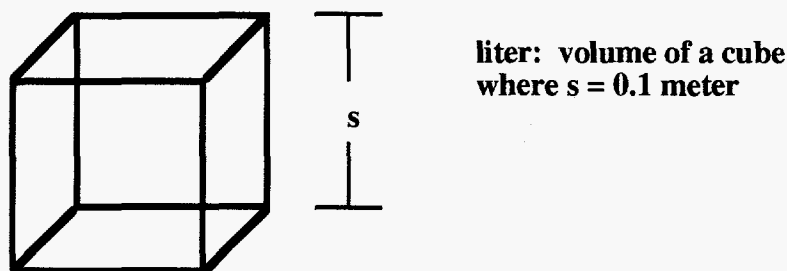
Figure 3: Definition of the liter.

The fourth kind of unit which was used to measure area was called the **are** (pronounced *air*). It was defined as the area of a square ten meters on each side. This unit is discussed in more detail in Section 1.6.

10 meters

10 meters
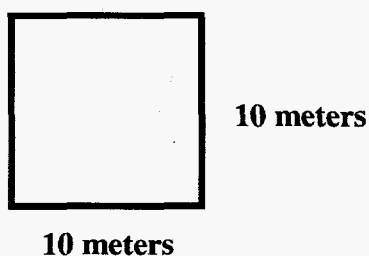
Figure 4: Definition of the unit of area, the *are*.

In 1799, the National Assembly formally adopted the new units, and the metric system was born.

It is interesting to observe the reaction of the French people toward adopting the metric system. The National Assembly did not make metric conversion mandatory, and reaction was mixed. Scientists liked the metric system, but the average person did not want to change. Most people preferred to stay with the older, more familiar units. With two systems of units being used, the situation in France was even more chaotic.

Finally, in 1837, the National Assembly decreed that effective January 1, 1840, only the metric system could be used. Fines were assessed if any other units were used. At last, the metric system had become the standard for France!

1.3   Structure of the Metric System

What are the advantages of the metric system over the inch-pound system?

The most important advantage of the metric system over the inch-pound system is its structure. The metric system is a *decimal system.*

A decimal system consists of a basic, or stem, unit. Smaller units are formed from the stem unit by **dividing** the size of the stem unit by a **power of 10** ($10^1 = 10$, $10^2 = 100$, $10^3 = 1000$, etc.). Larger units are formed by **multiplying** the size of the *stem unit by a power* of 10. Our monetary system is an example of a decimal system.

In the metric system smaller units, called **submultiples**, are formed by **dividing** the size of the stem units by a power of 10. Larger units, called **multiples**, are formed by **multiplying** the size of the stem units by a power of 10.

How are metric units named?

Names for submultiples and multiples are formed by combining the name of the stem unit with a prefix. (A prefix is a group of letters at the beginning of a word that adds to or quantifies its meaning.)

Six of the original metric prefixes and their meanings are given below.

Submultiples		Multiples	
deci	$10^{-1} = 0.1$	deka	$10^1 = 10$
centi	$10^{-2} = 0.01$	hecto	$10^2 = 100$
milli	$10^{-3} = 0.001$	kilo	$10^3 = 1000$

Combining prefixes with stem units gives:

Length

decimeter	0.1 meter	**deka**meter	10 meters
centimeter	0.01 meter	**hecto**meter	100 meters
millimeter	0.001 meter	**kilo**meter	1000 meters

Mass

decigram	0.1 gram	**deka**gram	10 grams
centigram	0.01 gram	**hecto**gram	100 grams
milligram	0.001 gram	**kilo**gram	1000 grams

Volume

deciliter	0.1 liter	**deka**liter	10 liters
centiliter	0.01 liter	**hecto**liter	100 liters
milliliter	0.001 liter	**kilo**liter	1000 liters

Thus, the original set of stem units for length, mass, and volume—meter, gram, and liter—has grown into a set of twenty-one units (three stem units, plus three submultiples and three multiples for each stem unit). The names of many of these units are probably already familiar to you.

Why are there different spellings for meter and liter?

Perhaps you have noticed that the words *meter* and *liter* (and unit names derived from these stem units) are sometimes spelled **metre** and **litre** (and millimetre, millilitre, etc.). *Metre* and *litre* are international spellings of these units, while *meter* and *liter* are spellings adopted for use in the United States by the Department of Commerce. The international spelling, which is used in virtually the rest of the world, uses the British Oxford dictionary's spelling (-re). The International Standards Organization, CGPM (described in Section 1.5) uses the -re spelling, but it does not require the use of the -re spelling. It is possible that after the United States converts to the metric system, we may eventually adopt the international spelling as well.

How are symbols for metric units formed?

In many applications it is convenient to use short forms of metric unit names, which are called **symbols** (NOT abbreviations). Symbols for submultiples and multiples are formed by combining the symbol for the prefix with the symbol for the stem unit, as shown below.

Length		Mass		Volume	
meter	m	gram	g	liter	L
millimeter	m m	milligram	m g	milliliter	mL
centimeter	cm	kilogram	kg		
kilometer	km				

Note that an uppercase (capital) L is used as the symbol for liter. Although either an uppercase L or lowercase l is permitted in the System of International Units (see Section 1.5), the United States recommends using an uppercase L because lowercase l is easily confused with the numeral 1.

Also note that the table above contains only nine of the twenty-one units listed on page 6. Symbols for units that are seldom used are not shown.

How do we convert from one unit to another in the same system?

Have you ever had to convert from one inch-pound unit to another? In the inch-pound system, conversion means multiplying or dividing by 3, 12, 16, or some other number because **the inch-pound system is not a decimal system**. The relationships between several commonly used inch-pound units are as follows.

Inch-pound units

12 inches = 1 foot	16 ounces = 1 pound	16 ounces = 1 pint
3 feet = 1 yard	2000 pounds = 1 ton	2 pints = 1 quart
5280 feet = 1 mile		4 quarts = 1 gallon

Converting from one inch-pound unit to another often requires substantial arithmetic (or the use of a calculator) as shown in the following example.

Example 1: Verify the conversion between the inch-pound units listed below:

a. 23 inches = 1.917 feet = 0.639 yard.

b. 11 ounces = 0.6875 pound.

c. 9 (fluid) ounces = 0.5625 pint = 0.0703 gallon.

Converting from one metric unit to another is very easy. It only involves moving the decimal point, which is equivalent to dividing or multiplying by a power of 10.

Example 2: Compare the ease of converting between the metric units below to the inch-pound conversions in Example 1.

a. 123 millimeters = 12.3 centimeters = 0.123 meter = 0.000123 kilometer.

b. 2520 milligrams = 2.52 grams = 0.00252 kilogram.

c. 975 milliliters = 0.975 liter.

Another interesting comparison between the inch-pound and metric system involves unit names. There is nothing in the names *inch*, *foot*, *yard*, and *mile* that gives any indication that these units are related to each other (unlike *millimeter*, *centimeter*, *meter*, and *kilometer*). This same comment can be made for units of mass (*ounce*, *pound*, *ton* vs. *milligram*, *gram*, *kilogram*) and units of volume (*ounce*, *pint*, *quart*, *gallon* vs. *milliliter*, *liter*). Note that the word *ounce* can mean a unit of mass (16 ounces is one pound) or a unit of volume (32 ounces is one quart). Clearly the inch-pound system is a much more difficult system to learn and use than the metric system.

Other metric prefixes

Metric prefixes are used to form unit names for multiples and submultiples of stem units. The six prefixes discussed above are not sufficient to handle modern scientific requirements for precise measurements. Many applications require units that are either much smaller or much larger than those using milli or kilo. Therefore, other prefixes have been added over the years. These prefixes, which are primarily used in scientific applications, are shown in the table below.

Prefix	Symbol	Size	
micro	μ	0.000 001	$= 10^{-6}$
nano	n	0.000 000 001	$= 10^{-9}$
pico	p	0.000 000 000 001	$= 10^{-12}$
femto	f	0.000 000 000 000 001	$= 10^{-15}$
atto	a	0.000 000 000 000 000 001	$= 10^{-18}$
zepto	z	0.000 000 000 000 000 000 001	$= 10^{-21}$
yocto	y	0.000 000 000 000 000 000 000 001	$= 10^{-24}$

Multiples

Prefix	Symbol	Size	
mega	M	1 000 000	$= 10^{6}$
giga	G	1 000 000 000	$= 10^{9}$
tera	T	1 000 000 000 000	$= 10^{12}$
peta	P	1 000 000 000 000 000	$= 10^{15}$
exa	E	1 000 000 000000 000 000	$= 10^{18}$
zetta	Z	1 000 000 000 000 000 000 000	$= 10^{21}$
yotta	Y	1 000 000 000 000 000 000 000 000	$= 10^{24}$

Symbols for these prefixes are formed by using the first letter of the prefix. The only exception is the symbol for the prefix *micro* which is the Greek letter μ (mu). This change is necessary because lowercase m is the symbol for the prefix *milli*.

Note that **symbols for prefixes larger than 1000 use uppercase letters**. Thus, changing from lowercase to uppercase (or uppercase to lowercase) changes the meaning of the symbol.

Some of these prefixes may already be familiar to you. Occasionally we see words such as **micro**second, **nano**second, and **mega**byte in computing. **Mega**watts is a term associated with electrical power. **Mega**bucks is sometimes used to describe large sums of money. The term **giga**watt was used in the movie *Back to the Future*.

1.4   Temperature Scales

Another common type of measurement is temperature. There are two commonly used temperature scales in the world, the Fahrenheit scale and the Celsius scale. Both scales are described below.

Fahrenheit scale

 In the United States we use the *Fahrenheit* temperature scale, which was developed in 1714 by a German physicist named Gabriel Fahrenheit. To develop his scale Fahrenheit started with a mixture of salt and water. He observed that the freezing point of this mixture was colder than the freezing point of pure water. Fahrenheit called the freezing point **zero degrees**. He also observed that the ratio of the temperature change from the zero point to the point at which pure water froze, and the change from the zero point to the temperature of human blood, was about 1 to 3. Fahrenheit called the temperature of human blood **96 degrees**. Thus, the temperature of the freezing point of water was 96/3, or 32 degrees. These measurements completely defined his scale.

We know Fahrenheit's estimate of the temperature of human blood was slightly in error, since normal body temperature is 98.6 degrees on his scale.

Water boils at sea level at 212 degrees on the Fahrenheit scale. (It is necessary to consider the boiling point at sea level since as you go up in altitude, water boils at a lower temperature.)

Celsius scale

A second temperature scale was invented in 1742 by a Swedish astronomer named Anders Celsius. Celsius selected as his reference points the freezing point and boiling point of water (at sea level). He called the freezing point **zero degrees** and the boiling point **one hundred degrees**. These points and the assigned values completely determined the Celsius scale. A comparison of the two scales is shown in Figure 5.

$212\ ^{\mathrm{o}}F$ ——— $100\ ^{\mathrm{o}}C$ boiling point

$98.6\ ^{\mathrm{o}}F$ ——— $37\ ^{\mathrm{o}}C$ normal body temperature

$68\ ^{\mathrm{o}}F$ ——— $20\ ^{\mathrm{o}}C$ room temperature

$32\ ^{\mathrm{o}}F$ ——— $0\ ^{\mathrm{o}}C$ freezing point of pure water
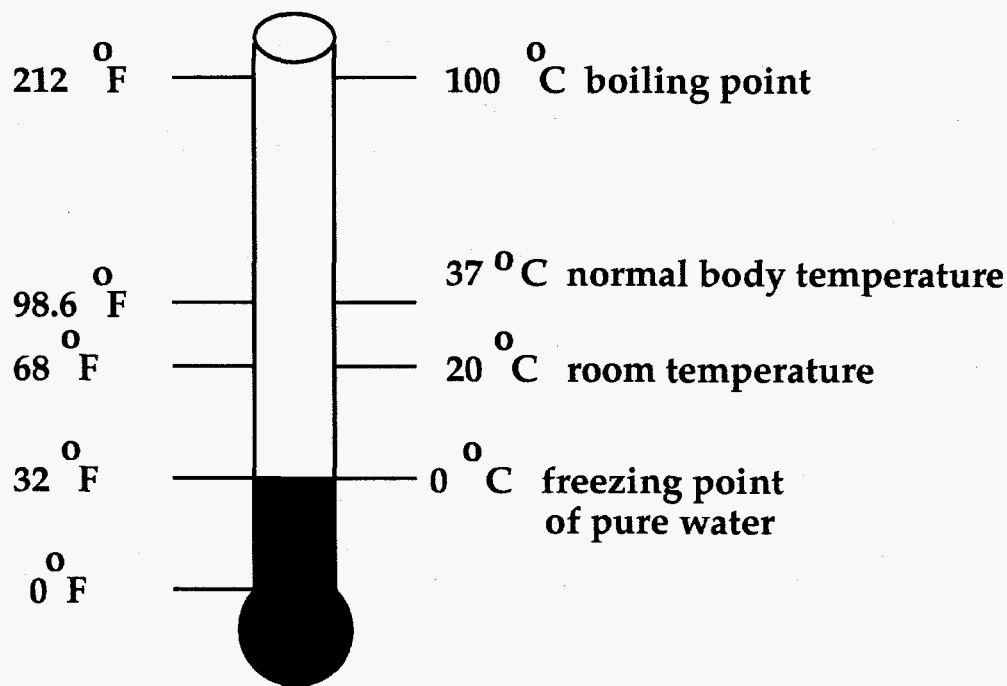
$0\ ^{\mathrm{o}}F$ ———

Figure 5   **Common Celsius temperatures.**

On the Celsius scale there are 100 steps, or degrees, between the freezing point and the boiling point of water. On the Fahrenheit scale it takes 180 degrees (212° - 32° = 180°) to go from the freezing point to the boiling point . Thus, **Celsius degrees are larger** by the ratio of 180/100, or 9/5. Simply stated, a 5-degree change on the Celsius scale equals a 9-degree change on the Fahrenheit scale.

Some reference points to help remember common Celsius temperatures are:

normal body temperature	37°
comfortable outdoor temperature	30°
room temperature (somewhat cool)	20°
freezing point of water	0°

Originally the Celsius scale was known as the centigrade scale. But the word *centigrade* is also the name of an angular measure used in some European countries. In 1948, the official name was changed to the Celsius scale in honor of its inventor.

Converting between the Fahrenheit and Celsius temperature scales

The formula for converting from Fahrenheit to Celsius is:

C = (5/9)∗(F - 32)

where F is the temperature in degrees Fahrenheit and C is the temperature in degrees Celsius. The formula for converting from Celsius to Fahrenheit is:

F = [(9/5)∗C] + 32

The following examples illustrate how to use these formulas.

Example 3: Find the Celsius temperature that corresponds to 68 °F.

C = (5/9)∗(68 - 32) = (5/9)∗(36) = 20

Thus, 68 °F corresponds to 20 °C.

Example 4: Find the Fahrenheit temperature that corresponds to 10 °C.

F = [(9/5)∗10] + 32 = 18 + 32 = 50

Thus, 10 °C corresponds to 50 °F.

1.5   System of International Units

In 1875, an historic event in metrology (the science of measurement) occurred. The **Treaty of the Meter** was signed by seventeen nations, including the United States. (As of March 31, 1991, forty-six countries had signed the treaty.) The Treaty of the Meter set up an organization for determining international standards. This organization has three parts:

- Conférence Générale des Poids et Mesures (CGPM)
- Comité International des Poids et Mesures (CIPM)
- Bureau International des Poids et Mesures (BIPM)

CGPM consists of delegates from all member nations, and meets about every five years. It makes final decisions on standards and policy for the System of International Units.

CIPM consists of eighteen members, each belonging to a different nation. It functions like a board of directors, and it is responsible for the operation of the international laboratory, BIPM.

BIPM, located at Pavillon de Bretueil just outside Paris, is the international laboratory responsible for establishing standards and scales of measurement, and carrying out and coordinating the determinations relating to fundamental physical constants.

BIPM and CIPM work closely with standards organizations in member nations. In the United States, that means NIST. NIST headquarters is located in Gaithersburg, Maryland, which is just outside Washington, DC.

Redefining the meter

The first problem encountered by CGPM was to decide what to do about the definition of the meter. By 1875, it was known that the original measurement of the great circle distance from the north pole to the equator was in error by over 2000 meters. CGPM had two choices:

- Keep the definition of the meter the same and change its length.
- Keep the length of the meter the same and change its definition.

CGPM chose the latter, and in 1889 the meter was officially defined as the distance between two scratches on a prototype bar made from a platinum-iridium alloy. As a result, the metric system was no longer based on a fact of nature. (Since 1889 the definition of the meter has been changed twice. These definitions are given in Appendix A.)

CGPM also changed the fundamental unit of mass from the gram to the kilogram. (However, names for smaller and larger units of mass continued to be based on prefixes combined with the gram.) A kilogram was defined as the mass of a prototype made from a platinum-iridium alloy.

Adding new units

Over the years, it has been necessary for CGPM to expand both the number and kinds of units in their system, and many new units have been added.

In 1954, CGPM divided its system of units into three classes:

- base units
- derived units
- supplementary units.

There are seven base units, and they are listed below:

Base units

Quantity measured	Name	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
luminous intensity	candela	cd
amount of material	mole (added in 1971)	mol

Many of the base units are used primarily in science, and they are not discussed here. However, for completeness, the formal definition of each base unit is given in Appendix A.

There are two supplementary units:

Supplementary units

Quantity measured	Name	Symbol
angles in the plane	radian	rad
solid angles	steradian	sr

The definitions of these units are given in Appendix A.

There are many kinds of derived units. Derived units are formed from combinations of base units and/or supplementary units. Some examples of derived units are given in the table below:

Examples of derived units

Quantity measured	Unit	Symbol
area	square meter	m^2
volume	cubic meter	m^3
speed	meters per second	m/s
density	mass per cubic meter	kg/m^3

Derived units with special names

Some derived units that have special names are shown below.

Examples of Derived Units with Special Names

Quantity Measured	Name	Definition	Symbol
force (mass times acceleration)	newton	1 kg·m/s^2	N
pressure (force per unit area)	pascal	1 N/m^2	Pa
energy (force times distance)	joule	1 N·m	J
power (energy per unit time)	watt	1 J/s	W

We discuss these units in more detail in Section 1.6.

Naming the system of units

In 1960, CGPM named their system of units **Le Système International d'Unités**, or the **System of International Units**, which is abbreviated **SI** in all languages.

SI is the modern metric system!

When we use the words *metric system*, we are referring to SI.

Over the years a number of versions of the metric system have evolved. One way in which versions differed was in the set of base units. One obsolete version of the metric system was known as the **cgs system**. The cgs system used the centimeter, gram, and second as base units. Units derived from these base units, such as the erg and dyne, are to be avoided. SI evolved from the **mks system** (meter-kilogram-second).

SI is a coherent system

SI is a **coherent** system of units. In a coherent system each unit is either a base unit or is formed by multiplying and/or dividing base units (and/or supplementary units) without involving any numeric factor other than one (1). Coherency greatly simplifies the relationships between SI units because there are no multiplying factors.

However, sometimes coherent units are not a very convenient size. This fact may be illustrated by the SI unit of pressure, the pascal. Standard air pressure for the tires on a car is slightly above thirty pounds per square inch. This pressure expressed in pascals would be over 200,000! A more convenient unit for tire pressure is the kilopascal (1000 pascals). Thus, multiples and submultiples of coherent units will be used in many applications. Examples of coherent units and commonly used multiples and submultiples are given in Section 1.6.

Non-SI Units that are used with SI

Some non-SI units have been approved for use with SI units. These units include minute (min), hour (h), day (d), and degree (°), minute (') and second (") relative to angles.

1.6   Other Units

Conversion to the metric system means that SI units—along with multiples and submultiples—will be used in many applications. Examples of these SI units are given below.

Area

The SI unit of area is the **square meter** (m^2). Square meters are used to measure areas of buildings, small fields, rooms, and similarly-sized regions.

Another unit of area is the hectare (ha). The name **hectare** comes from the prefix hecto (meaning 100) and the stem unit *are*, or hectoare, where the "o" has been dropped. (Recall that an *are* was defined as the area of a square 10 meters on a side.) Thus, a hectare is equal to 10,000 square meters. SI prefers the term **square hectometer** (hm^2) to hectare. Hectares (or square hectometers) will replace acres. One hectare is about 2.47 acres.

Other commonly used units of area are the **square centimeter** (cm^2), **square millimeter** (mm^2), and **square kilometer** (km^2).

Volume

The SI unit of volume is the **cubic meter** (m^3). For everyday use, such as an amount of milk purchased at a grocery store, a cubic meter is rather large. A more convenient size is the liter. It takes 1000 liters to make one cubic meter.

Another commonly used unit of volume is the **milliliter**. Since a milliliter is the volume of a cube that is one-hundredth of a meter on each edge, a milliliter is the same volume as a cubic centimeter. It takes 1000 milliliters to make a liter, and 1,000,000 milliliters to make a cubic meter.

Liters will replace quarts and gallons. Milliliters will replace (fluid) ounces. Most food containers sold in inch-pound sizes (such as the gallon, quart, pint, and 12-ounce cans) also show the equivalent volume in metric units, such as liters or milliliters.

In Section 1.2 it was noted that the liter was used to measure volumes of fluids. Volumes of dry material (such as sand, concrete, flour, etc.) are measured in cubic meters, cubic centimeters, or cubic millimeters.

Speed

The SI unit of speed is **meter per second** (m/s). However, in metric countries the speed of an automobile is usually expressed in kilometers per hour. Speedometers on most cars

sold in U. S. have both miles per hour (mph) and kilometers per hour (km/h) scales. A speed of 100 km/h is about 62 mph.

Density

Density is defined as mass per unit volume. The SI unit of density is **kilogram per cubic meter** (kg/m^3). This turns out to be a very small unit of density (about the density of Styrofoam™). Water has a density of about 1000 kg/m^3.

Another commonly used unit of density has been **grams per cubic centimeter** (g/cm^3). Because there are 1,000,000 cubic centimeters in a cubic meter, and 1000 grams in a kilogram, an object with a density of 1 g/cm^3 could be descibed as having a density of 1000 kg/m^3.

Force

Force is defined as mass times acceleration. The base unit of mass is the kilogram, and the coherent unit of acceleration is meter per second squared. Thus, the SI unit of force is **kilogram meter per second squared** ($kg\ m/s^2$). This unit of force is called a **newton** (N).

A force we deal with every day is the force of gravity. The acceleration due to gravity is about 10 meters per second squared. Therefore, the force of gravity acting on a one kilogram mass is about 10 newtons. A force of one newton is approximately equal to the force required to hold up a mass of about 100 grams (about the mass of a small apple).

Pressure

Pressure is defined as force per unit area. The SI unit of pressure, the **pascal** (Pa), is a force of one newton on an area of one square meter (1 Pa = 1 N/m^2). A pascal is a very small unit of pressure, and the **kilopascal** (kPa), which is 1000 pascals, is often a more convenient size.

In the inch-pound system, a familiar unit of pressure is pounds per square inch, or psi. (In this case, the pound is a unit of force, not mass.) One pound per square inch is just under 7000 pascals, or 7 kilopascals. Kilopascals will replace pounds per square inch.

Energy

Energy, or work, can occur in several different forms. Mechanical energy (work) is defined as force times distance moved. A force of one newton applied for a distance of one meter is the coherent unit of energy. This unit is called a **joule** (J). Thus, one joule is

$$1\ J = 1\ N \cdot m$$

Other forms of energy (kinetic, potential, electrical, etc.) use an equivalent definition of the joule.

One unit of energy commonly used in the inch-pound system relative to food is the Calorie (which is actually 1,000 calories). This unit will be replace by the kilojoule.

Power

Power is energy expended per unit time. The SI unit of power is the **watt** (W). One watt is defined as 1 joule per second.

$$1 \text{ W} = 1 \text{ J/s}$$

This is the same unit commonly used for electrical power.

1.7   Questions:

1. Public Law 100-418 stated that the Federal government must begin using metric units in business transactions by _____.

2. The system of units currently used in the U. S. is called the _____.

3. The metric system was developed in _____ (name of country) about _____ years ago.

4. The metric system is a _____ system, like our system of money.

5. In a decimal system, smaller and larger units are formed from a basic, or stem, unit by dividing or multiplying the size of the stem unit by a power of _____.

6. The original metric system consisted of units for _____, _____, _____ and _____.

7. The names of these units were _____, _____, _____ and _____.

8. What is the meaning of the following prefixes?
    a.   centi   _____
    b.   milli   _____
    c.   kilo   _____

9. What is the symbol for each of the following metric units?
    a.   meter_____   gram_____   liter_____
    b.   centimeter_____   milligram_____   milliliter_____
    c.   millimeter_____   kilogram_____
    d.   kilometer_____

10. Complete the following table:

    _____mm = _____cm = ___275____m = _____km

    _____mg = ___237.5___g = _____kg

    ___1250____mL = _____L

11. What is the Fahrenheit temperature that corresponds to 37 °C?

12. What is the Celsius temperature that corresponds to 14 °F?

13. What are the three categories of SI units?

14. Why was the original definition of the meter changed?

15. What is the name of the Federal agency that works with the international standards organization?

16. What is the abbreviation for the System of International Units?

17. What is the name of the treaty that gave an organizational structure to the development of an international standard for measurement?

18. What is meant by a coherent unit?

19. What is the coherent SI unit of energy?

20. What was the definition of the kilogram established in 1889?

Part 2: Applying the Metric System

2.1 Becoming Familiar with the Size of Metric Units

Becoming comfortable with the metric system requires developing a good picture of the size of commonly used metric units. In this section we help to develop these pictures.

Length

The stem unit for length is the **meter**. A meter is 39.37 inches long, or a little longer than a yard, about a yard plus the length of a piece of chalk.
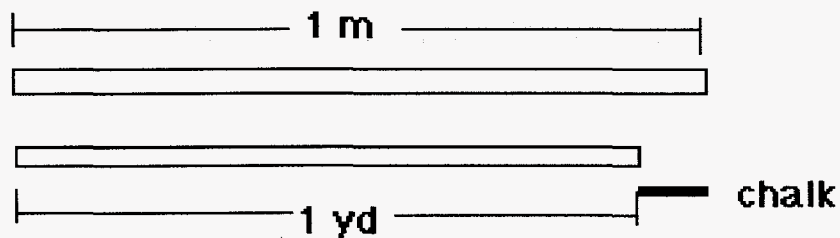
Figure 6: Meter (about a yard plus the length of a piece of chalk).

A **centimeter** is one-hundredth meter. It takes 2.54 centimeters to make one inch, or about 30 centimeters for a foot. A centimeter is about the width of the nail on your little finger.

Figure 7: Centimeter (about the width of the nail of your little finger).

A **millimeter** is one-thousandth of a meter, or one-tenth of a centimeter. A millimeter is about the thickness of a dime.
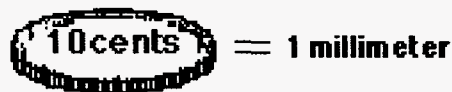
Figure 8: Millimeter (about the thickness of a dime).

A **kilometer** is 1000 meters, or about 5/8ths of a mile. If a mile is four times around a track, a kilometer is about $2^1/_2$ times around a track.
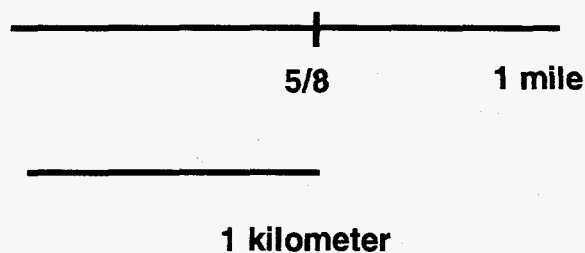
5/8   **1 mile**

1 kilometer

Figure 9:   **Kilometer (about 5/8ths of a mile).**

A 10 kilometer race is slightly more than 6 miles; 40 kilometers is about 25 miles.

Mass

The stem unit of mass is the **gram**. A gram is a very small mass. The contents of a package of *Sweet 'n Low* ™ (or *Equal*™) has a mass of 1 gram.
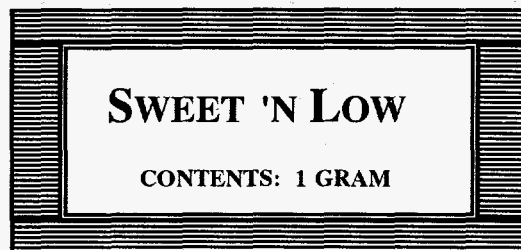
SWEET 'N LOW

CONTENTS: 1 GRAM

Figure 10:   **Gram (the mass of a package of artificial sweetener).**

A paper clip also has a mass of about one gram. A nickel has a mass of about 5 grams. It takes about 454 grams to make a pound.

A **milligram** is a very, very small mass. To picture the size of a milligram, empty the contents of a package of artificial sweetener onto a dish and imagine dividing up the contents into 1000 equal parts. One of those parts is a milligram.

Medications are often prescribed in milligrams.

A **kilogram** is 1000 grams. To picture one kilogram, take two one-pound packages of butter or margarine plus another quarter-pound stick. Cut a little bit off the end of the stick. This is approximately one kilogram. One kilogram is about 2.2 pounds.
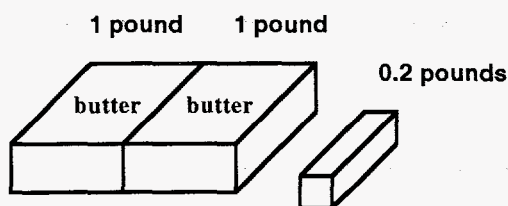
1 kilogram = 2.2 pounds

Figure 11:   Kilogram (about 2.2 pounds)

Volume

The stem unit for volume is the **liter**. A liter is a little larger than a quart. A liter contains 33.8 fluid ounces, while a quart is only 32 ounces.
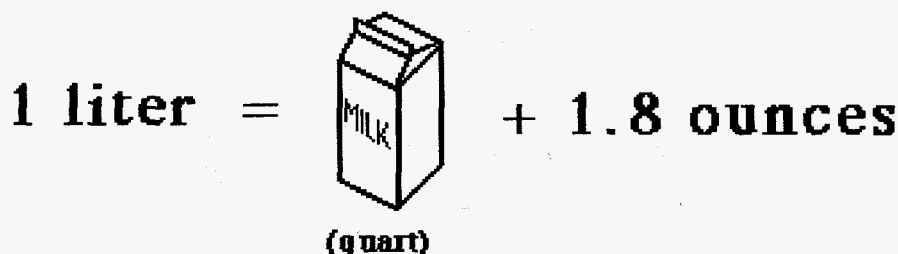

Figure 12:   Liter (about a quart and a quarter of a cup).

A **milliliter** is one-thousandth of a liter. It takes about 5 milliliters to make a teaspoon.

teaspoon

1 milliliter = 1/5 teaspoon

Figure 13:   Milliliter (about 1/5th of a teaspoon).

2.2 Applying the Metric System I: Unit Conversion

To learn the metric system, it is usually best to avoid converting between inch-pound and metric units. However, during the transition period, it may be necessary in many jobs to convert between systems. This section is designed to help you in the conversion process.

There are two levels of conversion. The first level is often called *exact** conversion. Exact conversion is quite easy to accomplish since it involves multiplying the given number of units in one system by the appropriate conversion factor to get the number of units in the other system.

A more sophisticated level of conversion between inch-pound and metric units involves concern about significant digits, precision, accuracy, and tolerance. This level of concern goes far beyond an introduction to the metric system, but the need to consider more sophisticated conversions can be illustrated quite easily. This need stems from the following common-sense rule:

Rule: In all conversions between measurement systems, accuracy should be neither sacrificed nor exaggerated.

To illustrate the application of this rule, consider the following problem:

Problem: Convert 40 inches to centimeters.

Since we are given a length in inches, we need to look up the conversion factor from inches to centimeters. In Appendix B we see

1 inch = 2.54 centimeters

Multiplying both sides of the above equation by 40 gives,

40*1 inch = 40*2.54 centimeters = 101.6 centimeters.

In an exact conversion, we would say 40 inches equals 101.6 centimeters.

But what does a measurement of 40 inches really mean? One interpretation is that the true length of the object being measured is between 35 and 45 inches, and we are rounding the measurement to the nearest 10 inches. In this case, when we convert 40 inches to centimeters, an answer of 101.6 centimeters implies a much more accurate measurement. A more appropriate solution would be to round the answer to the nearest 10 centimeters, which would give the solution as 100 centimeters.

A second interpretation is that 40 inches means that the true length of the object being measured is between 39.5 and 40.5 inches, and the original measurement was rounded to the nearest inch. In this case, a more appropriate answer would be to round 101.6 centimeters to the nearest centimeter, so the solution would be 102 centimeters.

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* The conversions are not exact in a mathematical sense because not all of the conversion factors are exact.

Thus, there are three possible answers:

- 100 cm (if 40 inches was rounded to the nearest 10 inches)
- 102 cm (if 40 inches was rounded to the nearest inch)
- 101.6 cm (if 40 inches was rounded to the nearest 0.1 inch)

A brief description of significant digits, precision, accuracy, and tolerance plus a couple of examples involving tolerances are contained in Appendix C. For a more complete discussion of this subject the reader should consult guidelines available from standards organizations, such as American Society for Testing & Materials (ASTM).

To help with simple conversion problems we have included several examples of exact conversion.

Exact conversions from inch-pound into metric units.

Example 5: Change 11 inches to millimeters.

Since we are given a length in inches, use the value in the table in Appendix B that says:

1 inch = 25.4 millimeters.

To compute the metric equivalent of 11 inches, multiply both sides of the above equation by 11.

11*1 inch = 11*25.4 millimeters = 279.4 millimeters.

11 inches = 279.4 millimeters

Example 6: Convert 16 feet 7 inches to meters.

16 feet 7 inches = 16 7/12 feet = 16.583 feet.

From Appendix B,

1 foot = 0.3048 meter.

To compute the metric equivalent of 16.583 feet, multiply both sides of the above equation by 16.583.

16.583*1 foot = 16.583*0.3048 meters = 5.054 meters.

16.583 feet = 5.054 meters

Example 7: Convert 245 miles to kilometers.

From Appendix B,

1 mile = 1.6093 kilometers.

To compute the metric equivalent of 245 miles, multiply both sides of the above equation by 245.

245*1 mile = 245*1.6093 kilometers = 394.28 kilometers.

| 245 miles = 394.28 kilometers |

Example 8: Convert 1 pound 5 ounces into grams.

1 pound 5 ounces = 1 5/16 pounds = 1.3125 pounds.

From Appendix B,

1 pound = 453.6 grams.

To compute the metric equivalent of 1.3125 pounds, multiply both sides of the above equation by 1.3125.

1.3125*1 pound = 1.3125*453.6 grams = 595.4 grams.

| 1.3125 pounds = 595.4 grams |

Example 9: Convert 125 pounds into kilograms.

From Appendix B,

1 pound = 0.4536 kilogram.

To compute the metric equivalent of 125 pounds, multiply both sides of the above equation by 125.

125*1 pound = 125*0.4536 kilograms = 56.7 kilograms.

| 125 pounds = 56.7 kilograms |

Example 10: Convert 12 (fluid) ounces into milliliters.

From Appendix B,

1 ounce = 29.57 milliliters.

To compute the metric equivalent of 12 ounces, multiply both sides of the above equation by 12.

12*1 ounce = 12*29.57 milliliters = 354.84 milliliters.

| 12 ounces = 354.84 milliliters |

Example 11: Convert 45 square yards to square meters.

From Appendix B,

1 square yard = 0.8361 square meter.

To compute the metric equivalent of 45 square yards, multiply both sides of the above equation by 45.

45*1 square yard = 45*0.8361 square meter = 37.62 square meters.

45 square yards = 37.62 square meters

Example 12: Convert a pressure of 30 pounds per square inch into kilopascals.

From Appendix B,

1 pound per square inch = 6.8948 kilopascals.

To compute the metric equivalent of one pound (force) per square inch, multiply both sides of the above equation by 30.

30*1 pound per square inch = 30*6.8948 kilopascals = 206.8 kilopascals.

30 pounds per square inch = 206.8 kilopascals

Exact conversions from metric into inch-pound units

Example 13: Change 5 millimeters into inches.

Since we are given a length in millimeters, use the value in the table in Appendix B that says:

1 millimeter = 0.03937 inch.

To compute the inch-pound equivalent of 5 millimeters, multiply both sides of the above equation by 5.

5*1 millimeter = 5*0.03937 inch = 0.197 inches.

5 millimeters = 0.197 inch

Example 14: Convert 40 kilometers to miles.

From Appendix B,

1 kilometer = 0.62137 mile.

To compute the inch-pound equivalent of 40 kilometers, multiply both sides of the above equation by 40.

40*1 kilometer = 40*0.62137 mile = 24.85 miles.

40 kilometers = 24.85 miles

Example 15: Convert 8510 grams into pounds.

From Appendix B,

1 gram = 0.0022046 pound.

To compute the inch-pound equivalent of 8510 grams, multiply both sides of the above equation by 8510.

8510*1 gram= 8510*0.0022046 pound = 18.76 pounds

| 8510 grams = 18.76 pounds |

Example 16: Convert 525 kilograms into pounds.

From Appendix B,

1 kilogram = 2.2046 pounds.

To compute the inch-pound equivalent of 525 kilograms, multiply both sides of the above equation by 525.

525*1 kilogram = 525*2.2046 pounds = 1157.4 pounds.

| 525 kilograms = 1157.4 pounds |

Example 17: Convert 75 milliliters into ounces.

From Appendix B,

1 milliliter = 0.033814 ounce.

To compute the inch-pound equivalent of 75 milliliters, multiply both sides of the above equation by 75.

75*1 milliliter = 75*0.033814 ounce = 2.536 ounces.

| 75 milliliters = 2.538 ounces |

Example 18: Convert 230 square centimeters into square inches.

From Appendix B,

1 square centimeter = 0.155 square inch.

To compute the inch-pound equivalent of 230 square centimeters, multiply both sides of the above equation by 230.

230*1 square centimeter = 230*0.155 square inch = 35.65 square inches.

| 230 square centimeters = 35.65 square inches |

Example 19: Convert 95 kilometers per hour into miles per hour.

From Appendix B,

1 kilometer per hour = 0.62137 mile per hour.

To compute the inch-pound equivalent 95 kilometers per hour, multiply both sides of the above equation by 95.

95*1 kilometer per hour = 95*0.62137 mile per hour = 59 miles per hour.

95 kilometers per hour = 59 miles per hour

2.3 Applying the Metric System II: Rules for Using SI Units and Symbols

In many jobs it will be necessary to use metric unit names and metric symbols in reports and on drawings. There are a number of rules for metric usage developed by SI and other standards organizations such as ISO (International Organization for Standardization), ANSI (American National Standards Institute), and IEEE (Institute of Electrical and Electronics Engineers). Some of the more common rules are described below.

1. Use a space between a digit and a symbol.

    Right: 243 cm

    Wrong: 243cm

2. Don't use a symbol unless it is preceded by a number. (Write out the unit name.)

    Right: Miles will be replaced by kilometers.

    Wrong: Miles will be replaced by km.

3. Don't use a period after a symbol unless it is at the end of a sentence.

    Right: The room was 12,200 mm by 6,100 mm.

    Wrong: The room was 12,200 mm. by 6,100 mm.

4. Don't mix symbols and unit names in compound units.

    Right: meters per second

                    m/s

    Wrong: meters/second

                    m per s

28

5. The same symbol is used for singular and plural.

    Right: 10 cm

    Wrong: 10 cms

6. Unit names are treated like common nouns and do not begin with a capital letter unless they begin a sentence.   (exception: Celsius).

    Right: One kilometer is equal to one thousand meters.

               The temperature dropped five degrees Celsius in one hour.

    Wrong: One Kilometer is equal to one thousand meters.

               The temperature dropped five degrees celsius in one hour.

7. Symbols should be written in upright type (not in italics) despite the nature of the text around the symbol.

    Right: *The window is 240* mm *wide.*

    Wrong: *The window is 240 mm wide.*

8. Use at most one slash in compound units.

    Right: The newton is a unit of force that is defined as a mass of one
               kilogram accelerated at the rate of one meter per second squared, or
               $1 \text{ N} = 1 \text{ kg·m/s}^2$.

    Wrong: The newton is a unit of force that is defined as a mass of one
               kilogram accelerated at the rate of one meter per second per second,
               or $1 \text{ N} = 1 \text{ kg·m/s/s}$.

9. Don't mix inch-pound abbreviations and metric symbols

    Right: The volume of the tank was 100 m^3.

    Wrong: The volume of the tank was 100 cu. m.

There are differences between the way things are done in the United States and the way they are done in other countries. In order to establish world-wide standards, it means some things may have to be done differently.

To illustrate differences in customs, consider how we write large numbers. In the United States we use commas as separators. For example, the number seven hundred ninety-two thousand, four hundred fifty-eight would be written 792,458. In many other countries this

number would be interpreted as seven hundred ninety-two and four hundred fifty-eight thousandths, because the comma is used as a *decimal marker*. (We use a period as a decimal marker and call it a *decimal point*.) An alternate way to achieve separation is to use spaces instead of commas. In this case the above number would be written 792 458. The use of spaces is an international standard to avoid confusion between using commas as separators and as decimal markers. It is not necessary to use a space in a four-digit number (e.g. 1234 is correct, not 1 234). The use of spaces as separators instead of commas is not an SI standard. It is included here to assist people working with companies and agencies involved in international markets.

Paper Sizes

Another example of an international standard that will soon impact us involves paper. In the United States the current standard size is $8^{1}/_{2}$ by 11 inches. The international size (specified by ISO) is known as **A4** which is 210 mm by 297 mm (about $8^{1}/_{4}$ by $11^{5}/_{8}$ inches). The Federal government is moving toward the use of A4 paper. For example, soon the Congressional Record will be printed on A4 paper. Also, NIST has issued technical reports on A4 paper.

A4 is actually only one size in a series of paper sizes called the A-Series. The A-Series starts with a sheet which is 841 by 1189 millimeters. This size is called A0. Sizes A1, A2, A3, A4, etc. are formed by cutting the previous size in half as shown in Figure 14. In each case the ratio of the short side to the long side is $1:\sqrt{2}$.
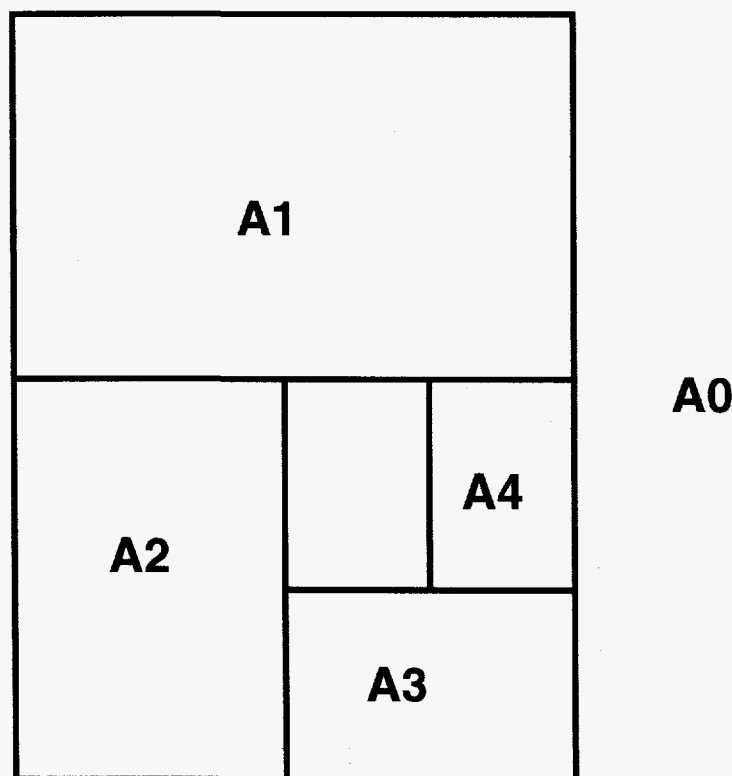

Figure 14: A-Series of paper sizes

Most copy machines and computer printers are already equipped to handle A4 paper with a simple change of a setting.

One problem with converting to A4 paper is that old file cabinets which are only 11 inches wide are narrower than the paper.

In addition to the A-Series there is a B-Series of paper sizes. The B-Series is frequently used for posters, wall charts, etc. There is also a C-Series which is for envelopes.

2.4   Applying the Metric System III: Planning the Conversion

There are two general philosophies of conversion:
- soft conversion
- hard conversion.

Soft conversion means simply changing from inch-pound units to metric units without changing product sizes or packaging. In essence, soft conversion involves only changing the label on a product or container to give the size or amount in metric units rather than inch-pound units. Soft conversion tends to reduce the up-front costs of conversion, but it may not save as much as hard conversion in the long term.

Hard conversion means changing product design and/or packaging to convenient metric sizes.

The difference between soft and hard conversion can be illustrated by considering typical sheet of paneling found in most lumber stores. The standard size for a sheet is 4 feet by 8 feet. The metric equivalent of 4 feet by 8 feet is 1220 millimeters by 2440 millimeters. Soft conversion would not change the size of the sheet of paneling; it would simply label it 1220 millimeters by 2440 millimeters. Hard conversion would change the size to a more convenient number of millimeters, such as 1200 millimeters by 2400 millimeters. The difference in size means that new sheets of paneling may not work well in remodeling jobs because they would be somewhat smaller than the sizes of paneling or wallboard they are replacing. But the smaller size could be used in new construction that was designed and built to metric standards.

Hard conversion offers a company, or an entire industry, a chance to rethink how it operates, and provides a rare opportunity to start over in many ways. Often, new ideas on how to solve old problems are found. Sometimes the new ideas aren't even related to metric conversion, but they often provide solid cost-cutting techniques. Hard conversion may mean a higher up-front cost, but it may offer significant long-term savings and efficiencies.

Soft conversion and hard conversion represent two extremes. Often a company (or a laboratory) will make compromises, depending on product and customer needs. Sometimes a compromise is prudent, but it is important not to sacrifice long-term benefits for a short-term bottom line effect.

Measuring the cost of conversion

Measuring the cost of conversion is sometimes difficult. Suppose, for example, that a company wishes to convert to metric units and establishes a metric conversion budget for each department. Suppose also that a department manager needs new equipment such as computers for several employees. If the manager uses metrication as an excuse to purchase the computers, is the cost really due to metrication?

Another important question involving cost is, how well has the metrication effort been defined and planned? A clear understanding of metric needs and careful planning can have a significant impact on the ultimate metric conversion costs. Careful planning can be a vital factor in the success or failure of metric conversion.

In general, experience shows that metric conversion has been neither as costly nor as traumatic as feared—provided it was carefully planned and implemented.

2.5 The Metric System in the United States

Converting to the metric system has been a nonstop argument in the United States for almost 200 years. At times the argument has been quite intense, and then it would cool off. Usually scientists sided with the supporters of metrication. Those opposed to metrication sometimes used religious arguments, particularly in the later part of the 19th Century.

Legislative efforts involving metrication date back long before the Metric Study Act (1968), the Metric Conversion Act (1975), and Public Law 100-418 (1988) discussed in Section 1.1. Some of the more interesting legislative efforts are described below.

In 1790 President George Washington reminded Congress of its responsibility to fix standards of weights and measures. The matter was referred to Secretary of State Thomas Jefferson. Jefferson proposed a decimal system of measurement with a new *foot* and a new *inch*. But Jefferson's plan was not adopted.

In 1821 Secretary of State John Quincy Adams submitted a report to Congress on weights and measures. In his report Adams listed the advantages of the metric system (based on a fact of nature, single unit for weight, single unit for volume, decimal basis, and its uniform and precise terminology). Adams also noted that the metric system had not been popular with the people of France. In the end, Congress took no action on the Adams report.

On July 28, 1866 Congress made it lawful to use metric units in contracts and other documents, but there was no sentiment to force people to switch from inch-pound units.

In the last half of the 19th Century there were 14 bills written involving metric conversion, plus one resolution in the House of Representatives. Many of the bills died in committee and never came up for a formal hearing.

In 1902 Congress came very close to passing legislation that would have required all government departments to use the metric system. This bill was sponsored by

Congressman Southard from Ohio, and debate on the bill was scheduled for July. As July approached, it appeared as if passage was certain. However, after a lengthy debate on terminating military rule in Cuba, Congress suddenly adjourned before the Southard bill was introduced. Before Congress reconvened, opposition forces banded together and protested the conversion because of the costs involved. Because opposition was strong and passage was uncertain, Southard decided to withdraw the bill.

It is interesting to speculate on what would have happened if Congress had stayed in session long enough to pass the Southard bill. It is highly probable that in the 1990s the U. S. would be using only the metric system. This means that you would not be taking a course on the metric system today because you would have been using metric units all of your life. Instead you may be enrolled in a history course that examined a rather unwieldy and inefficient system of measurement used long ago in the United States, the inch-pound system.

What will happen in the United States?

If metrication has failed in the past, will it succeed now? Why is today different from even the mid-1970s when metrication was rejected by most people?

The biggest difference between metrication efforts today and in the past is that now metrication is an economic necessity. Because the rest of the world is metric, and world markets demand metric goods, we need to convert in order to remain a powerful force in the world economy.

Second, Public Law 100-418 made metrication mandatory for the Federal government (in most areas) by the end of fiscal year 1992. Although this date has passed and the Federal government is not yet using metric units exclusively, significant progress has been made. Federal agencies are developing and implementing metric transition plans, and progress should gradually accelerate.

Although Public Law 100-418 does not mandate conversion by the general population, the Federal government spends hundreds of billions of dollars each year. Companies (plus state and local governments) that deal with the Federal government will have to begin using metric units. Therefore, Public Law 100-418 impacts a large fraction of the population. The impact is going to come first in the workplace, where there is a strong incentive to learn metric units because you want to continue getting paid.

Third, most people are already familiar with the names of the commonly used metric units. There are metric products we use daily, such as 35-millimeter film and 2-liter soft drink bottles. Medication is prescribed in grams, milligrams, and sometimes milliliters. Metric units are on almost all food labels. We need metric tools to work on our cars.

One of the most aggressive agencies in metric conversion is the Department of Transportation. The Federal Highway Administration plans to convert Federal highways by 1996. This commitment is having a ripple effect with state departments of transportation and utilities such as telephone companies that work closely with highway departments.

There is no good time to convert to the metric system. But the longer conversion is postponed, the more difficult it will be. Thus, the real issue today is not **if** the United States is going to convert; instead, the two most relevant questions are: When will the conversion be complete? And how painful will it be?

2.6   Questions

1. What is the size of this booklet in millimeters?

2. What is the width of the palm of your hand in centimeters?

3. What is the size of your waist in centimeters?

4. How tall are you in centimeters?

5. If you flew from Washington, DC. to San Francisco, about how many kilometers would you get in your frequent flier program?
   a. 1000 km   b. 2000 km   c. 3000 km   d. 4000 km   e. 5000 km

6. How many grams are there in a pound of sugar?

7. What is the mass of this booklet in grams?

8. What is your mass in kilograms?

9. What is the approximate mass of a small car (in kilograms)?

10. How many kilograms are there in a large Thanksgiving turkey?

11. How many milliliters are there in a cup?

12. How many milliliters are there in a quart?

13. How many liters are there in a gallon?

14. How many cubic meters are there in 12 cubic yards?

15. How many liters are there in a cubic meter??

References:

1. *A METRIC AMERICA: A decision whose time has come*, Report to the Congress, July 1971, National Bureau of Standards Special Publication 345.

2. *Prepare Now for a Metric Future*, by Frank Donovan, Weybright and Talley, New York, 1970.

3. *Standard Practice for the Use of the International System of Units*, E380, 1989a, American Society for Testing & Materials, 1916 Race Street, Philadelphia, PA 19103.

4. *The Science of Measurement, A Historical Survey*, Dover Publications, Inc., New York, 1988.

Appendix A: Formal Definitions of Base Units and Supplementary Units

Base Units

Listed below are the formal definitions of the seven base units that were listed in Section 1.5.

meter In 1960 the definition of the meter was changed from the distance between two scratches on a platinum-iridium bar to 1,650,763.73 wavelengths of the orange-red line of krypton 86.

In 1983 it was changed again to the distance light travels in (1/299,792,458)th of a second.

These changes did not change the length of the meter, but they increased the precision of the measurement.

kilogram The mass of a prototype bar made of platinum-iridium.

second The duration of 9,192,631,770 cycles of the radiation associated with a specified transition of the cesium-133 atom.

ampere The current that, if maintained in each of two long parallel wires separated by one meter in free space, would produce a force between the two wires (due to their magnetic fields) of 2×10^{-7} newton for each meter of length.

kelvin The fraction 1/273.16 of the thermodynamic temperature of the triple point of water (water exists as a solid, liquid, and vapor).

candela The luminous intensity in a given direction of a source that emits monochromatic radiation of a frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

mole The amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12.
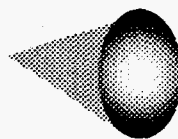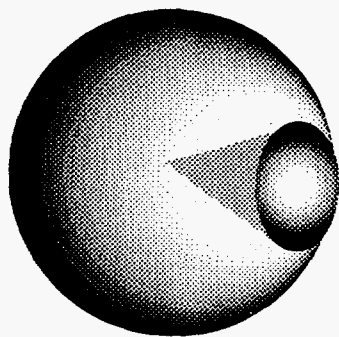
Supplementary Units

radian   A radian is an angle between two radii of a circle that yields an arc length of the circle equal to the length of the radius, as shown in the figure below.
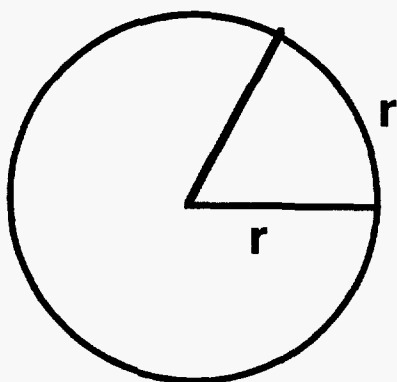
steradian   A solid angle that gives a surface area equal to the square of the radius of the sphere as shown in the figure below.

$$area = r^2$$

Appendix B: Conversion Tables

Converting to the metric system will result in using new units to express sizes. The table below shows the new metric unit, typical inch-pound units it will replace, and the relationship in size. This table can be used to convert from metric to inch-pound units.

Table 1   Metric to Inch-pound

Metric	Symbol	Inch-pound	Relationship
meter	m	foot, yard	1 meter = 39.37 inches
centimeter	cm	inch, foot	1 centimeter = 0.3937 inch
millimeter	mm	inch	1 millimeter = 0.03937 inch
kilometer	km	mile	1 kilometer = 0.62137 mile
gram	g	ounce	1 gram = 0.03527 ounce
gram	g	pound	1 gram = 0.0022046 pound
milligram	mg	ounce	1 milligram = 0.00003527 ounce
kilogram	kg	pound	1 kilogram = 2.2046 pounds
liter	L	quart, gallon	1 liter = 1.05669 quarts
milliliter	mL	ounce	1 milliliter = 0.033814 ounce
square meter	m^2	ft^2, yd^2	1 square meter = 10.764 square feet
square centimeter	cm^2	ft^2, in^2	1 square centimeter = 0.155 square inch
square millimeter	mm^2	in^2	1 square millimeter = 0.00155 square inch
hectare	ha	acre	1 hectare = 2.471 acres
cubic meter	m^3	cubic foot or yard	1 cubic meter = 35.31 cubic feet
cubic centimeter	cm^3	cubic inch	1 cubic centimeter = 0.06102 cubic inch
meters per second	m/s	feet per second	1 meter per second = 3.28 feet per second
kilometers per hour	km/h	miles per hour	1 kilometer per hour = 0.62137 mile per hour

The following table can be used to convert from inch-pound to metric units.

Table 2   Inch-pound to Metric

Inch-pound	Metric Unit	Relationship
foot	meter	1 foot = 0.3048 meter
inch	millimeter	1 inch = 25.4 millimeters
inch	centimeter	1 inch = 2.54 centimeters
yard	meter	1 yard = 0.9144 meter
mile	kilometer	1 mile = 1.6093 kilometers
ounce	gram	1 ounce = 28.3495 grams
pound	gram	1 pound = 453.6 grams
pound	kilogram	1 pound = 0.4536 kilogram
ounce	milliliter	1 ounce = 29.57 milliliters
pint	milliliter	1 pint = 0.473 liter
quart	liter	1 quart = 0.946 liter
gallon	liter	1 gallon = 3.785 liters
square foot	square meter	1 square foot = 0.0929 square meter
square inch	square centimeter	1 square inch = 6.451 square centimeters
square yard	square meter	1 square yard = 0.8361 square meter
acre	hectare	1 acre = 0.4047 hectare
feet per second	meters per second	1 foot per second = 0.3048 meter per second
miles per hour	kilometers per hour	1 mile per hour = 1.609 kilometers per hour
pound per square inch	kilopascals	1 pound per square inch = 6.8948 kilopascals

Appendix C: Conversions Involving Significant Digits, Precision, Accuracy, and Tolerance

A more sophisticated level of conversion between inch-pound and metric units involves significant digits, precision, accuracy, and tolerance, which are defined below (source: ASTM E380-89A).

Significant digit – a prescribed decimal place that determines the amount of rounding off to be done. Nonzero digits are significant, and zeros may or may not be significant.

Example C1: Significant Digits

The number 0.00345 has three significant digits (3, 4, and 5). The number 200,100 may have been rounded to the nearest hundred (in which case there are four significant digits); or rounded to the nearest 10 (in which case the 0 to the right of the 1 is significant), or it may not have been rounded (all six digits are significant).

Precision – the degree of mutual agreement between individual measurements.

Example: The measurement 200.4 mm is precise to the nearest tenth of a millimeter.

Accuracy – the degree of conformity of a measured or calculated value to some recognized standard or specified value.

Tolerance – the total amount by which a quantity is allowed to vary; that is, the difference between the maximum and minimum limits.

The following rule relates to conversion between systems.

Rule: In all conversions the number of significant digits retained should be such that accuracy is neither sacrificed nor exaggerated.

When tolerances are specified, there are two methods for rounding as specified by ASTM.

Method A: Round to values nearest each limit.

Method B: Round to values inside the limits.

Example C2:   Convert the following measurement to millimeters.

$$1.950 \pm 0.016 \text{ inches}$$

(The true measurement lies between 1.934 and 1.966 inches.)

Since 1 inch = 25.4 mm, converting the limits to millimeters gives 49.1236 (which is 25.4∗1.934) and 49.9364 (which is 25.4∗1.966) millimeters. The tolerance is 0.32 inch, which lies between 0.4 and 0.04 inches. The ASTM table says to round to the nearest 0.01 millimeter. Thus, using method A, the minimum and maximum values would be 49.12 and 49.94 millimeters.

Using method B, the minimum and maximum values would be 49.13 and 49.93, which are in the interior of the interval [49.1236, 49.9364].

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Policy and Procedure

Vol. 4, No. 8   February 4, 1974

Laboratory Policy on Conversion to the Use of the International Metric System

The modern metric system known as the International System of Units (SI) will become the predominant system of measurement in the United States. In anticipation of the widespread usage of SI units in science and engineering, both in industry and in government, this Laboratory adopts the following policy on the use of SI:

Policy

SI units will be the primary system of measurement at Lawrence Livermore Laboratory and will be used in all reporting and handling of engineering and scientific data and in engineering design and fabrication.

Policy Implementation

Implementation of this policy will be on a reasonable and cost effective basis. A Laboratory Metrication Committee chaired by Jack Pearson of Mechanical Engineering has been appointed to coordinate and guide the Livermore effort. In cooperation with the committee, each division or department will establish its own appropriate schedule for a changeover to the use of SI measurement units.

The conversion to SI at the Laboratory will be coordinated with the conversion within the AEC and the integrated contractors.

-R. E. Batzel
Director

LAWRENCE LIVERMORE LABORATORY

RESTATEMENT OF LABORATORY POLICY ON CONVERSION TO THE USE OF THE INTERNATIONAL METRIC SYSTEM

The Laboratory established a Metric Policy in 1974 which stated:

> "The modern metric system known as the International System of Units (SI) will be the primary system of measurement at Lawrence Livermore Laboratory and will be used in all reporting and handling of engineering and scientific data and in engineering design and fabrication."

Though this policy was not completely implemented, metric transition now has a new priority based upon a Presidential Executive Order, DOE Order 5900.2 and Public Law 100-418 which designate the metric system of measurement as the preferred system of weights and measures for U.S. trade and commerce.

Continued implementation of this policy will be on a reasonable and cost effective basis. Roger Werne, Associate Director for Engineering, will be the Laboratory contact for this effort. A LLNL Metric Transition Committee is being formed and Dae (Danny) Chung will serve as the Metric Coordinator and chair of this committee. In cooperation with the committee, each organization will establish its own appropriate schedule for a changeover to the use of SI measurement units.

Duane C. Sewell
Deputy Director

Lawrence Livermore National Laboratory